PULSED POWER FOR THE ELECTRA KrF LASER*

J.D. Sethian, S.P. Obenschain, M. Myers, I. Smith†, D. Weidenheimer†, V. Carboni†, J. Kishi†, D. Morton†, J. Pearce†, B. Bowen†, L. Schlitt‡, J. Fockler§, O. Barr**
Plasma Physics Division, Naval Research Laboratory, Washington DC

Abstract

Electra is a rep-rate Krypton Fluoride (KrF) laser that will be used to develop the technology required for an Inertial Fusion Energy (IFE) Power Plant. Electra will use the same type of architecture as the Nike 60 cm amplifier [1], e.g. double-sided electron beam pumping of the laser gas, but it will run at 5 Hz and use technologies that can meet the IFE requirements for efficiency, durability, and cost. The size of Electra was chosen to be small enough to be manageable, yet large enough to confidently scale the developed technologies to a power plant-size system. We will build two 5 Hz pulsed power systems for Electra. The first system is based on existing technology. It will be built in the first year of the program and will allow us to start development of the laser components early in the second year. The second system will use advanced components. It will take 3-4 years to build, and will develop the technologies that can meet the IFE requirements. It will be installed on Electra for an integrated test.

I. INTRODUCTION

Direct drive with a Krypton-Fluoride (KrF) laser is a promising approach for Fusion Energy: The Sombrero Power Plant study [2] showed a KrF based system could lead to an economically attractive power plant; direct drive target designs under development at NRL [3] show potential for the high gain required for IFE; and the Nike laser at NRL has demonstrated that a multi-kilojoule, e-beam pumped, KrF laser can be built and that it can produce the very spatially uniform laser needed for a high gain target [4].

The goal of the Electra program is to develop the technology required for Inertial Fusion Energy (IFE). As a first step, we have drafted our requirements from the Sombrero Study and the High Gain Target Designs. The requirements relevant to the pulsed power are shown in Table I. Electra will be 10-100 times smaller than a power plant laser beam line, but it will be large enough to develop the required technologies. Electra will have a 30 cm x 30 cm optical aperture, a laser output of 400–700 J, and run at 5 Hz. The main amplifier will be pumped with two 30 cm x 100 cm electron beams, each with V = 500 kV, I = 110 kA, and τ = 100-300 nsec.

Table I.
Pulsed Power Requirements for a KrF IFE laser

Parameter	Qty
System efficiency	6-7%
Rep-Rate	5 Hz
Durability (shots) [a]	3×10^8
Cost of entire laser [b]	$225/J(laser)
Cost of pulsed power[b]	$5.00/J(e-beam)

[a] Shots between major maintenance (~ 2.0 years)
[b] 1999 dollars. Sombreo study (1992) gave $180/Joule (laser) and $4.00/Joule (e-beam)

The main components that need to be developed are: a durable and efficient pulsed power system; a durable electron beam emitter; a long life, transparent pressure foil structure, or hibachi (to isolate the laser cell from the electron beam diode); a recirculator to cool and quiet the laser gas between shots; and long life optical windows. The pulsed power will be discussed in this paper. The other components have been discussed elsewhere [5]. They have all been partially developed, but separately and not necessarily in a parameter range for IFE. Electra will be built by integrating each component as it is developed.

We will build two complete pulsed power systems for Electra. The first, discussed in Section II, will be based on existing technology and will be finished by the winter of 2000. This system will run at 5 Hz for 10^5 shots between refurbishment. It will not meet the efficiency or the durability requirements, but it will give us a vehicle to develop the emitter, pressure foil support, laser gas recirculator, and optics. The advanced pulsed power is described in Section III. We anticipate that it will take three years to develop. It will use technologies that can meet the IFE requirements. When completed it will be integrated into Electra.

* This work sponsored by the US Department of Energy
† Pulse Sciences, Inc, San Leandro, CA
‡ Leland Schlitt Consulting services, Livermore, CA
§ James Fockler Consulting, Castro Valley, CA
** Pharos Technical Enterprises

0-7803-5498-2/99/$10.00©1999 IEEE.

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1999	**N/A**	**-**

4. TITLE AND SUBTITLE	
Pulsed Power For The Electra Krf Laser	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Plasma Physics Division, Naval Research Laboratory, Washington DC**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

Electra is a rep-rate Krypton Fluoride (KrF) laser that will be used to develop the technology required for an Inertial Fusion Energy (IFE) Power Plant. Electra will use the same type of architecture as the Nike 60 cm amplifier [l], e.g. double-sided electron beam pumping of the laser gas, but it will run at 5 Hz and use technologies that can meet the lFE requirements for efficiency, durability, and cost. The size of Electra was chosen to be small enough to be manageable, yet large enough to confidently scale the developed technologies to a power plant-size system. We will build two 5 Hz pulsed power systems for Electra. The first system is based on existing technology. It will be built in the first year of the program and will allow us to start development of the laser components early in the second year. The second system will use advanced components. It will take 3-4 years to build and will develop the technologies that can meet the IFE requirements. It will be installed on Electra for an integrated test.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

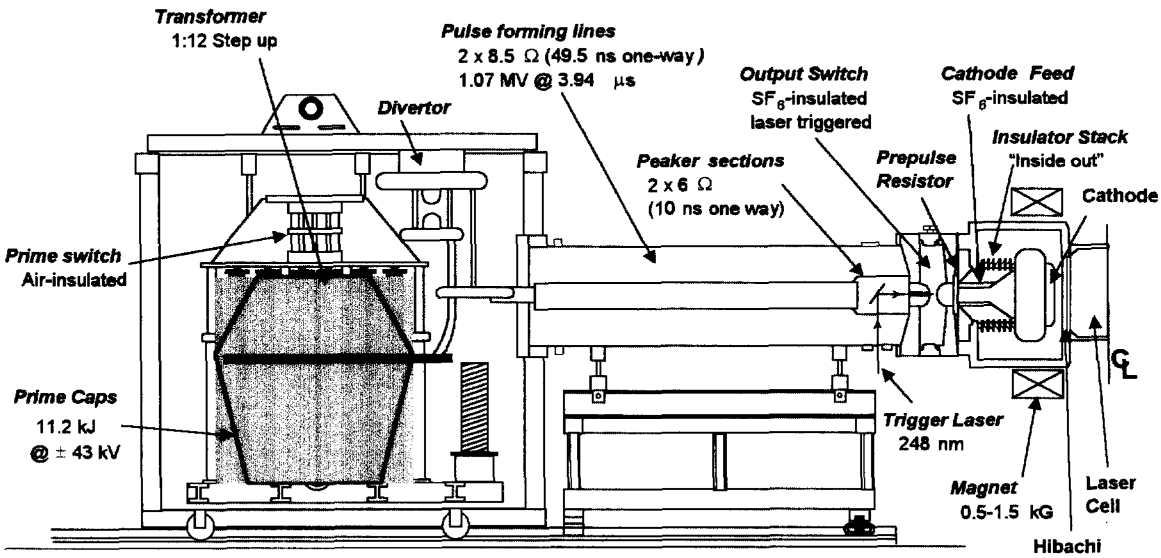

Figure 1. First Generation Pulsed Power System. One side is shown. The other side is a mirror image

II. FIRST GENERATION PULSED POWER

A. *System Architecture*

One side of the first generation pulse power system is shown in Figure 1. A capacitor bank feeds the primary side of a step-up auto-transformer. The secondary side resonantly charges two parallel water pulse forming lines (PFL). The PFLs are switched out by laser triggered gas output switches. The power flows from each PFL, through its own "inside-out" vacuum insulator, to a common cathode. A laser-triggered divertor switch serves both to reduce post pulse transients and to protect against failures in the system. The prime switch/step up transformer arrangement is based on the AIRIX [6] and DAHRT injector [7], whereas the water PFLs, output switches, and vacuum insulator are taken from the Nike 60 cm amplifier [1]. A lumped parameter circuit is shown in Figure 2.

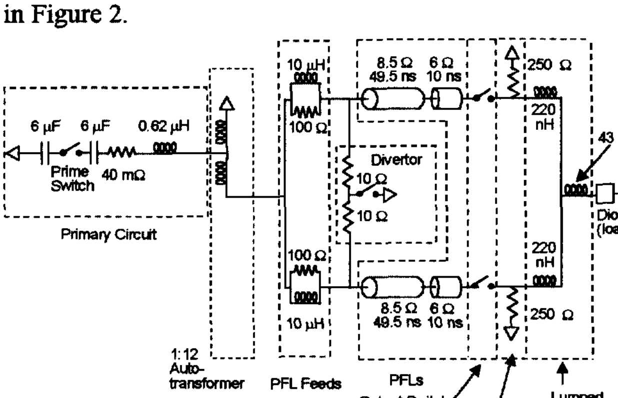

Figure 2. Circuit of the First Generation System.

B. *Prime Power Circuit*

The primary circuit includes the capacitor bank, transformer, PFL feeds and divertor switch. The components are contained in a tank of insulating oil. The primary capacitor bank is a 3 parallel by 2 series array of 2.0 μF, 50 kV, capacitors, and stores ~11.2 KJ at the operating level of +/– 43 KV (86% of the capacitor rated voltage). Normal reversal on each capacitor is kept to 20% by switching the PFLs at 98% of peak. The peak primary current is ~80 kA with a charge transfer of 0.8 C. Design life (90% survival) of the capacitors is expected to be > 10^7 shots.

As in AIRIX and DAHRT, the bank is switched with a flowing air switch based on the AVCO "Vortex" design [8]. Cooling is done by blowing air through the spark gap and flowing oil past the external surfaces. The Schwartzkopf K-33 tungsten-copper alloy electrodes should last ~10^5 shots based on scaling electrode erosion rates [9]. With UV illumination we expect the jitter to be ~ 5 ns.

The transformer is an iron core auto-transformer designed for 5 Hz operation with a turns ratio of 1:12. The core is reset between shots by continuous DC current from an external power supply.

C. *Pulse Forming Lines*

The two water-dielectric PFLs are fed from the transformer through a parallel combination of a 100 Ω resistor and a 10 μH inductor. These isolate the PFLs from each other and damp post-pulse oscillations and transients. The single pass transit time of each PFL is 59.5 nsec, but each line is actually comprised of two sections: a 49.5 nsec long, 8.5 Ω line, followed by a 10 nsec long, 6 Ω "risetime peaker" section. The peaker

impedance gives a good compromise between risetime and pulse flatness. The PFLs are switched out at 1.07 MV at 3.94 μs. This is 98% of the peak voltage of 1.09 MV at 4.34 μs. The t_{eff} is ~1.5 μs. With a total stressed area of ~40,000 cm^2 for all four PFLs (i.e. both sides) the electrical stress on the negative (inner) conductor is 40% of breakdown. For the positive (outer) conductor it is 27%.

D. Output Switch

The output switch is based on the Nike 60 cm amplifier design [1], but has been modified for long life and 5 Hz operation. Changes from Nike include: lower electric fields (46 kV/cm vs. 77 kV/cm along the high voltage diaphragm interface), more uniformly graded fields along the diaphragms, reduced fields at the electrode-diaphragm triple points, and debris traps in the outer conductors. Continually filtered SF_6 is flowed through the switch for both debris removal and cooling. We anticipate the K-33 switch electrodes will have a lifetime of 10^5 shots.

All four switches are triggered at ~ 65% of self-break by a quadrupled YAG laser (λ=266 nm). The laser energy into each switch is ~ 20 mJ with an intensity of 10 GW/cm^2. Based on Nike the jitter should be about 1 ns (1σ). The laser beam goes through a window in the peaker outer conductor, propagates through the water, and enters a sealed cavity inside the peaker inner conductor. The cavity is filled with dry N_2, and has a mirror and lens to direct the beam through a hole in the high voltage electrode. The light is focussed at the gap midpoint.

A 250 Ω, 25 pF radial liquid resistor is placed immediately after the output switch. Its function is to reduce the prepulse on the diode to less than 5 kV/cm. The sodium thiosulfate electrolyte is flowed through the resistor at 10 gpm in normal operation. The flow can be increased to create a resistive load for testing.

E. SF_6 Section and Vacuum Insulator

Electra uses an "inside-out" vacuum insulator to minimize the inductance of the feed region. See Figure 1. The feed region is insulated with 100 psig SF_6. The insulator is composed of seven, 2.54 cm thick acrylic rings and six 0.6 cm thick metal grading rings.

The cathode feed was shaped to achieve a near uniformly graded insulator stack. A fully three-dimensional calculation was not possible so the geometry was analyzed in two-dimensions using two different cross-sections. Figure 3 shows one of those views, from which it can be seen that the electric field along the insulator is uniform to within 3.3%. Using the $Ft^{1/2}A^{1/10}$ formula for flashover, and taking the combined area of all four insulator stacks (i.e. both sides) the system is running at only 35% of breakdown. As there are really four stacks of seven rings each, the probability of a total stack flashing is estimated [10] to be less than 10^{-10}.

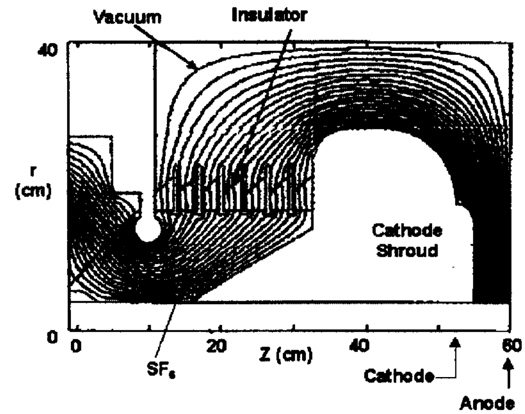

Figure 3. Potential plot of SF_6 Section, Insulator & Cathode.

Extensive calculations were performed to insure the system was not overstressed, even with cathode turn-on times as long as 40 ns. (At 40 ns the diode voltage during the transient can be as high as 725 kV, whereas during the main pulse it is 500 kV) The criteria we used was to keep the field below 80kV/cm for the main pulse and 100kV/cm for the transient. In our design the fields on the grading rings do not exceed 60kV/cm, or 95kV/cm, respectively.

F. Diode Box/Magnet

The diode box and cathode shroud were sized to minimize the overall dimensions, but maintain the field criteria cited above. The box has two 1500 l/s cryopumps. These pumps should keep the diode pressure at 10^{-3} Torr at a 5 Hz rep-rate if we use the velvet cathode used in Nike. As Electra will require advanced cathodes with much lower out gassing rates (such as the one used in RHEPP [11]) the operating pressure should be much lower. The electron beam is guided and prevented from self pinching with an external, water cooled magnet. The magnet is capable of 1.5 kG, or about three times the beam self field.

G. Divertor Switch

The divertor has two functions: In normal operation, it "clips" the tail of the pulse and reduces transients across the transformer. In abnormal operation, either because the prime switch prefires or the main switches fail to fire, it dissipates the energy in the circuit. One divertor switch controls both PFLs. The switch is based on the Blumlien switches used in DARHT [7]. It is SF_6 insulated and triggered with a KrF laser. In normal operation the output switch is fired first, and the divertor is fired 64 ns latter. In abnormal operation, a prefire detection circuit fires the laser within ~1.5 μs, and takes the voltage off the system rapidly. Note we can not use a YAG laser here because it requires a pre-triggering time of 150 μs.

H. Predicted Performance

The predicted diode power and voltage waveforms are shown in Figure 4. These were computed using a transmission line model. The diode power is 27 GW, and is flat to +/- 5% for 100 ns. The diode voltage is 494 kV +/- 5% during that period.

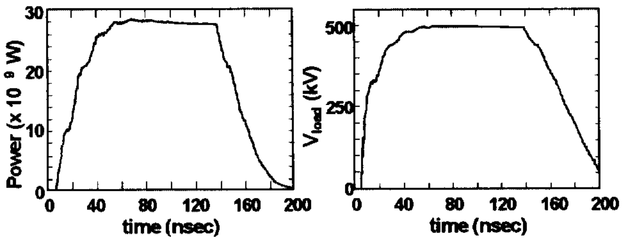

Figure 4. Predicted diode power (left) and Voltage (right).

III. ADVANCED PULSED POWER

The advanced pulsed power system requirements are given in Table I. We have allocated the 6-7% efficiency of the entire laser as follows: 80% for the pulsed power (wall plug to flat top electron beam), 80% for the hibachi, 10-12% for the intrinsic efficiency of KrF [12,13] and 95% for the ancillary components (e.g. gas recirculator). The Sombrero study shows the pulsed power should cost $5.00/Joule in present dollars. We take this as a soft goal, as the study needs to be revisited in light of the recent advances in KrF lasers and in high gain target designs.

After considering a wide variety of options, it appears that the most promising avenue to achieve the required durability is with a system that uses mostly solid state components. It seems the best approach is to have a specialized rotating machine and controlled rectifier charge a capacitive primary store, and then use a series of "compression" stages to increase the power by decreasing the transfer time. The present system of choice would be based on a magnetic compressor, as pioneered at LLNL [14] and more recently in the Sandia RHEPP modulator [15]. However there are some fundamental limitations to this approach. Meeting the cost and efficiency requirements using a magnetic compressor requires us to minimize number of stages. This is achieved by minimizing the downstream power gain, which in turn requires we minimize the primary store transfer time. Yet it is unlikely that a prime switch can be developed with a transfer time below 5 μsec. As the maximum economical power compression with a magnetic stage is about a factor of 3, this requires at least three stages of compression to achieve the several hundred nsec output pulse required for IFE. Accordingly we have identified two alternatives. Both represent a higher risk, but the payoff is high because they require less magnetic stages, and hence have the potential for higher efficiency and lower cost.

We discuss the pure magnetic compressor and the two options below. The designs are for a 100 kJ module with an electron beam output of 800kV, 165kA, 600 nsec. This is an appropriate size for a power plant-sized KrF beam line.

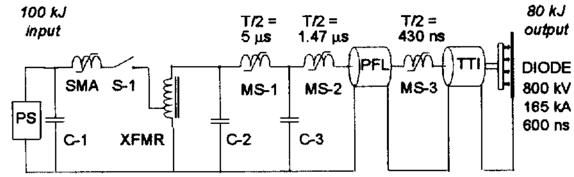

Figure 5. 100 kJ Magnetic Compressor Circuit.

A. Pure Magnetic Compressor

The currently preferred approach is shown in Figure 5. The rotating machine/rectifier Power Supply (PS) would charge the primary energy store capacitor (C-1). The prime switch (S-1), using a Saturating Magnetic Assist (SMA), would discharge the capacitor though a step up transformer (XFMR) on a timescale of 5 μs. Following the transformer are three compression stages. These use magnetic switches (MS-1 MS-2, MS-3), with the first two stages having water dielectric capacitors (C-2 and C-3), and the third a PFL. A transit time isolator (TTI) downstream of the final switch is necessary for charging the PFL, mitigating pre-pulse, and relaxing the component inductance requirements. The component that needs the most development is the primary switch. The most likely candidate, an advanced thyristor, will require the SMA for early di/dt management. An alternate approach is to use a thyratron, which would use the SMA to achieve extended lifetimes.

The efficiency of this system is estimated to be 80%. Moreover, applying the same costing methodology as in the Sombrero study [2], we get a preliminary cost of $6.10/ Joule, or just 12% higher than the Sombrero figure. We caution that we need to improve the accuracy of this estimate, but it gives us encouragement that this approach may be able to meet the IFE cost and efficiency requirements.

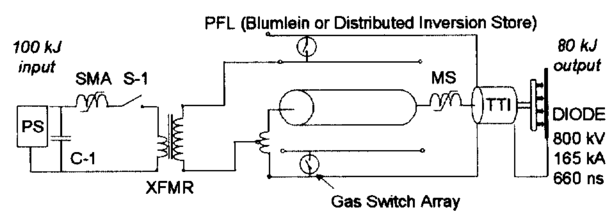

Figure 6. Advanced gas switch based system.

B. Advanced Gas Switch Option

In this approach, shown in Figure 6, we use an advanced Gas Switches Array (GSA) to switch or invert a triaxial, water dielectric, PFL. A magnetic switch (MS) at the output of the PFL serves as either a pre-pulse isolation switch (in the case of Blumlein operation) or as an output switch (in the case of a distributed inversion stage). This arrangement could allow longer primary transfer times which would relax the prime switch (S-1) requirements. It also reduces the number of transfer stages (and hence, magnetic switches) from 3 to 1 with a corresponding

reduction in cost. The efficiency of this system is also estimated to be 80%. Using the same costing guidelines as above, our preliminary estimate shows the cost could be as low as \$4.90/J. Again these numbers need to be refined, but this approach may be more likely to meet the cost requirements. The uncertainty here is the development of the advanced gas switch. Methods for dealing with the erosion of electrode material have been identified. These should give continuous operation for a few times 10^8, but they will need to be developed for this case. Insulator protection is also an issue and techniques that have previously kept insulators clean for the equivalent of millions of shots will be evaluated.

C. Advanced Marx PFN

Another possibility is to use an advanced Marx-Pulse Forming Network (PFN) [16]. Present concepts utilize multiple parallel sub-Marxes for inductance control, advanced PFN capacitor designs, saturating magnetic assist and photonically triggered solid state switches. The challenges are to achieve the compactness necessary to give a useable risetime and to develop the substantially advanced solid state switches. The payoff is large, as this approach combines the primary energy storage with pulse shaping, and hence could be the lowest cost, highest efficiency approach. Preliminary estimates suggest \$4.00/J in current dollars.

D. Electra Advanced Pulsed Power

We will determine which of these options to pursue with further research. This will include testing of components and concepts. When the best approach is identified, we will build a system for Electra. The Electra advanced power system would be on the order of 7 kJ, and hence not as large as the systems described above. This is because we first want to validate the technology, and a 100 kJ system would be too large a step. The voltage and current of the Advanced Pulsed Power System would be the same as for the First Generation System. We may, however, increase the pulse length to as much as 300 ns in order to study long term diode behavior.

IV. SUMMARY

The Electra laser will be built to develop the technologies required for Inertial Fusion Energy. We anticipate that this will be a five year program, culminating with a single integrated test of all the laser components.

V. REFERENCES

[1] J. D. Sethian, et al, "Large area electron beam pumped krypton fluoride laser amplifier," *Rev. Sci. Instrum*, 68, 2357, (1997).

[2] I.V. Sviatoslavsky, et al, "A KrF laser driven inertial fusion reactor "Sombrero," Fusion Technology, 21, 1470, (1992).

[3] S.E. Bodner et al, "Direct drive laser fusion; status and prospects," *Phys of Plasmas* **5**, 1901, (1998).

[4] S.P. Obenschain,, et al, "The Nike KrF laser facility: performance and initial target experiments," *Phys of Plasmas*, **3**, 2098 (1996).

[5] J.D. Sethian, et al, "KrF lasers for inertial fusion energy," Proc 17th IEEE Symp on Fusion Engineering, IEEE 0-7803-4226-7/98, p 593.

[6] J. Launspach, et al, "Recent results on the DAHRT and AIRIX 4 MV +/- 1%, 3.5 kA electron beam injectors," Tenth International Conference on High Power Particle Beams, San Diego, CA. 20-24 June, 1994. p.515.

[7] J. Fockler, et al, "A 4 MV ± 1% Flat-top electron diode driver," Proc. Eighth IEEE Pulsed Power Conference, p. 177 (1991).

[8] R. Limpaecher, et al, "An application of a high energy spark gap in a repetitive mode," Proc. Fifth IEEE Pulsed Power Conf, p 477 (1985).

[9] A. L. Donaldson, et al, "Electrode erosion phenomena in a high energy pulsed discharge," IEEE Trans on Plasma Sci, **PS-12**, 1984, pg 28.

[10] I.D. Smith, "Flashover of vacuum interfaces with many stages and large transit times," Proc. Tenth IEEE Pulsed Power Conf., p 558 (1995).

[11] S.D. Korovin, "Long lifetime metal-dielectric cathodes," Report AF-0416, High Current Electronics Inst, Tomsk, Russia (1993).

[12] A.E. Mandl et al, "KrF Laser Studies at High Krypton Density," Fusion Tech 11, 542 (1987).

[13] A. Suda, et al, Characteristics of an electron beam pumped KrF amplifier", Appl. Phys. Lett, 218 (1987).

[14] D.L. Birx, et al, "Experiments in magnetic switching," Proc. Third IEEE Pulsed Power Conference, p 226 (1981).

[15] L.X Schneider, et al, " Repetitive high energy pulsed power technology development," Proc, 14th Int Conf on Accelerators in Industry & Research, Nov 6-9, 1996 Denton Texas.

[16] J. Shannon, "A 500 kV rep-rate Marx Generator," Proc. Second IEEE Pulsed Power Conference, p 226 (1979).